HEAVIER AND LIGHTER LOAD RESISTANCE TRAINING TO MOMENTARY FAILURE PRODUCE SIMILAR INCREASES IN STRENGTH WITH DIFFERING DEGREES OF DISCOMFORT

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ABSTRACT: *Introduction:* It has been suggested that disparities in effort and discomfort between high- and low-load resistance training might exist, which in turn have produced unequivocal adaptations between studies. *Methods:* Strength responses to heavier load (HL; 80% maximum voluntary isometric torque; MVIT) and lighter load (LL; 50% MVIT) resistance training were examined in addition to acute perceptions of effort and discomfort. Seven men (20.6 ± 0.5 years, 178.9 ± 3.2 cm, 77.1 ± 2.7 kg) performed unilateral resistance training of the knee extensors to momentary failure using HL and LL. *Results:* Analyses revealed significant pre- to post-intervention increases in strength for both HL and LL, with no significant between-group differences ($P > 0.05$). Mean repetitions per set, total training time, and discomfort were all significantly higher for LL compared with HL ($P < 0.05$). *Conclusion:* This study indicates that resistance training with HL and LL produces similar strength adaptations, but discomfort should be considered before selecting a training load.

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There is a general consensus that there exists a need to maximally recruit motor units to optimize strength and hypertrophy adaptations to resistance training (RT).[1] Studies have suggested that, although there may be a submaximal threshold for effort,[2] training to momentary failure could optimize such recruitment, and thus adaptations.[3,4] Empirical research comparing heavier load (HL) and lighter load (LL) RT appears to generally support similar increases in strength and hypertrophy, so long as exercises are performed to momentary failure.[5–7] Nevertheless, this remains a contentious issue.[8–12]

Fisher *et al.*[9] recently hypothesized that disparity in outcome measures between studies may have been the result of differing degrees of *effort* as a result of the *discomfort* associated with training to momentary failure with LLs. For example, when training to momentary failure, effort (i.e., the amount of mental or physical energy being given to a task) should always be maximal, whereas discomfort (i.e., the physiological and unpleasant sensations associated with exercise[13,14]) may differ due to the increasing number of repetitions and longer time under muscular tension resulting from LL resistance training.[15,16] Indeed, effort is thought to originate from the primary motor cortex independently of peripheral afferent feedback,[14,17] and thus a differentiation of perceived effort from discomfort should be expected under certain conditions.

Smirnaul[18] illustrated this hypothesis by suggesting repetitive maximal contractions will induce a greater degree of discomfort than a single maximal contraction, even though effort would be the same (e.g., maximal). Therefore, it seems likely that a longer time under tension and/or higher volume of repetitions of submaximal exercise preceding a maximal effort/contraction may also serve to induce a higher degree of discomfort. We may logically consider that, when a person exercises to momentary failure, any reported values for perceived effort would be maximal. However, studies have previously reported submaximal, yet higher values for rating of effort when load[19] or repetitions[15] are increased. As such, it seems likely that, within these studies, participants have reported discomfort rather than effort. One example is the study by Shimano *et al.*,[20] where the highest values for rating of effort were reported after the lowest load condition for lower body exercise. It seems likely that participants in that study[20] may have been influenced by their discomfort rather than solely reporting their effort. If it is true that, if a person's discomfort has affected the effort value reported, then it is also possible that one's attempt to train to momentary failure may cease short of maximal effort due to a high degree of discomfort.

Conflation of perceptions of *effort* with *discomfort* means that interpretation of the perceptual responses to different loading conditions in RT is difficult with current methods. Differences in the acute experience during exercise may have implications for adherence, particularly if 2 interventions can produce similar adaptations with differing degrees of discomfort. With this in mind we considered the strength adaptations resulting from HL and LL RT to momentary failure while

Abbreviations: ATP, adenosine triphosphate; APMHR, age-predicted maximum heart rate; ES, effect size; HL, heavier load; ICC, intraclass correlation coefficient; LL, lighter load; MVIT, maximal voluntary isometric torque; NLMF, non-local muscular fatigue; PARQ, physical activity readiness questionnaire; P_i, inorganic phosphate; RM, repetition maximum; RPE-D, rating of perceived exertion for discomfort; RPE-E, rating of perceived exertion for effort; RPE, rating of perceived exertion; RT, resistance training; SI, strength index

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including the assessment of ratings of effort and discomfort arising from each condition using scales designed to permit their differentiation. We hypothesized that, although strength adaptations would be similar between groups, the LL group would report higher ratings of discomfort as a product of the increased volume of training preceding momentary failure.

METHODS

Study Design. In this study we aimed to compare the effects of a 6-week unilateral knee extensor RT program using HL (~80% maximal voluntary isometric torque; MVIT) or LL (~50% MVIT) loads to momentary failure. To avoid bias as a result of individual responses to training, we used a within-subject research design, where participants trained 1 leg using an HL and the contralateral leg using an LL. Use of this methodological approach is well represented in previous research[2,21] and allowed for control of between-participant confounding factors, including potential differences in perception of effort and discomfort. Both legs were trained in the same session for the 6-week duration, alternating the leg that was exercised first (HL or LL) to nullify any effect of continued central fatigue. Furthermore, an isometric testing condition was performed before and after a dynamic training intervention, which served to minimize skill acquisition (including the rehearsal of synchronous dynamic motor unit recruitment) of the testing method.[9,22]

Participants. An *a priori* power analysis of effect sizes for change in strength was conducted using effect sizes from a recent meta-analysis of RT research[23] to determine participant numbers (n) using effect size (ES) calculated using a Cohen d[24] of ~1.1–1.3 for improvements in strength. Participant numbers were calculated using G*Power.[25,26] These calculations showed the study conducted required 6 or 7 participants to meet the required power of 0.8 at an alpha value of $P < 0.05$ for identification of within-condition effects.

Upon approval from the relevant ethics committee (in accordance with the Helsinki Declaration of 1975; ethics code HESS#342), 7 recreationally active males were recruited (Table 1). All participants had previous RT experience, but had not been engaged in a structured program (e.g., ≥2 days/week) for the previous 6 months. All participants completed a physical activity readiness questionnaire (PARQ), signed informed consent, and were accepted for inclusion if they had no signs or symptoms of disease, no orthopedic injuries, and were not using any medication or performance-enhancing substances that could affect the study.

Table 1. Participants' characteristics

Characteristic	
Age (years)	20.6 ± 0.5
Height (cm)	178.9 ± 3.2
Body mass (kg)	77.1 ± 2.7
Body mass index (kg/m^2	24.1 ± 0.4

Data expressed as mean ± standard deviation.

Testing. All participants attended a familiarization session where, before any testing, they performed a standardized warm-up on a cycle ergometer (Ergomedic 874e; Monark, Uppsala, Sweden) for 5 minutes at up to 60% age-predicted maximum heart rate (APMHR). They were then seated in the knee extension machine, and the seat was adjusted to align the lateral epicondyle of the femur with the axis of rotation of a knee extension dynamometer (MedX, Ocala, Florida). The lower limbs were restrained to a pad (against which they would later push), and a hip belt was tightened to avoid unwanted movement of the pelvis when pushing through the knee extensors. A specific dynamic bilateral warm-up was then completed (80 lbs./~36 kg) using a 2-second–1-second–3-second (concentric–isometric–eccentric) repetition duration, for 10–15 repetitions, on the MedX knee extension machine. A practice isometric test was then performed unilaterally, for both left and right legs, at 3 joint angles: near-maximal knee flexion (e.g., 108°); near-maximal knee extension (e.g., 18°); and a midpoint between these 2 angles. This was to allow participants to become familiar with the experience of performing isometric testing as per MedX guidelines. MVIT was then measured at 7 joint angles (108°, 96°, 78°, 60°, 42°, 24°, and 18°) of knee flexion. Participants were asked to exhale as they built to maximal force over 2–3 seconds (to avoid performing a Valsalva maneuver), and then relax over a further 2–3 seconds.

After the familiarization testing, the dominant and non-dominant legs were assessed. This was done for further subdivision of grouping and allowed 4 of the participants to train their dominant leg with heavier (80% MVIT) and 3 to train the dominant leg with lighter (50% MVIT) loads, and *vice versa* for the non-dominant leg. This protocol was employed to control for strength adaptations between dominant and non-dominant legs. Familiarization with the rating of perceived exertion for effort (RPE-E) and discomfort (RPE-D), using 0–10 scales for scoring, was also provided during the familiarization and baseline testing sessions so that participants were clear on how the scales were anchored. For RPE-E (Fig. 1), participants were instructed as follows: "*The scale begins at*

HOW HARD DO YOU THINK YOU'RE WORKING?

0	NO EXERTION
1	EXTREMELY EASY
2	
3	EASY
4	
5	SOMEWHAT HARD
6	
7	HARD
8	
9	VERY HARD
10	MAXIMAL EFFORT

FIGURE 1. RPE-E scale for assessing perceived effort.

0 which is defined as no physical exertion is taking place. This can be likened to your perception of effort sitting on a machine but remaining motionless. The scale ends at 10 which is described as the maximum perceivable effort. This can be likened to your perception of effort when, despite putting forth as much exertion as you can, you cannot physically complete the activity being attempted." For RPE-D (Fig. 2) participants were instructed as follows: "*The scale begins at 0, which is described as no perceived discomfort. This can be likened to a perception of discomfort at a time where you feel no noticeable sensations relating to physical activity. The scale ends at 10, which is described as the maximum perceivable discomfort. This can be likened to a perception of discomfort where you could not imagine the sensations relating to physical activity being any more intense.*" Unpublished data from our laboratory show these scales have been validated to enable participants to differentiate clearly between perceptions of effort and discomfort and have been shown to be reliable.[27]

Maximal pre- and post-intervention testing was then performed using the machine set-up identified during the familiarization session, and the general warm-up (cycle task), specific warm-up (bilateral exercise), and unilateral isometric tests were performed as described previously. To assist in obtaining maximal effort, participants were given verbal encouragement throughout maximal testing. The MedX knee extension machine has a high test–retest reliability, with correlation levels reported at $r = 0.90–0.96$[28]; furthermore, we have high reliability within our own laboratories, with an intraclass correlation coefficient (ICC) = 0.926 [95% confidence interval (CI) 0.779–0.984].

Training. A supervised unilateral dynamic leg extension RT intervention was performed (1 day/week), on the same MedX apparatus used for testing for weeks 2–7 using a load of either 80% or 50% of MVIT (this was established based on the maximal isometric torque at 78°). All repetitions were performed through a full range of motion (18° to 108° of knee flexion). A low-frequency protocol was used to ensure that cumulative fatigue between exercise sessions did not affect effort or discomfort values reported, as well as to assess the efficacy of such a minimalist protocol. Participants performed repetitions to momentary failure and were requested to attempt a further repetition even when they thought it could not be accomplished. This was to ensure that momentary failure was reached. Participants performed 3 sets with each leg with 2-minute inter-set rest intervals[29,30] to allow adequate recovery.

Repetition duration was controlled at 2 seconds–1 second–3 seconds (concentric–isometric–eccentric), as described earlier. The loading remained constant throughout the duration of the intervention, and participants had 15 minutes of rest between exercise bouts before training the opposite leg.[31] Each week alternated between training the dominant and non-dominant leg first (and thus the HL and LL condition) to ensure systemic fatigue did not impact performance. Immediately after each set of exercise for each condition (HL or LL), each participant was asked to report their RPE-E and RPE-D[27] on 0–10 scales.

Statistical Analysis. Isometric force data were considered as a strength index (SI) as provided by the MedX clinical equipment. This has been described in previous studies,[2,32] where SI represents the area under a force curve created in each isometric test and accommodates potential increases or decreases throughout the entire strength curve for all test positions. This incorporates strength increases throughout the entire range of motion and negates biasing data by seeking average increases or decreases, or only considering specific joint angles.

The independent variable considered was the training condition (HL or LL), and the dependent variables included pre-strength, the absolute change in strength due to the intervention, average RPE-E, average RPE-D, average repetitions per set, change in repetitions performed for each set from beginning (week 1) to end (week 6) of

HOW MUCH DISCOMFORT DO YOU FEEL?

0	NO DISCOMFORT
1	MINOR DISCOMFORT
2	
3	MILD DISCOMFORT
4	
5	MODERATE DISCOMFORT
6	
7	SEVERE DISCOMFORT
8	
9	VERY SEVERE DISCOMFORT
10	MAXIMAL DISCOMFORT

FIGURE 2. RPE-D scale for assessing perceived discomfort.

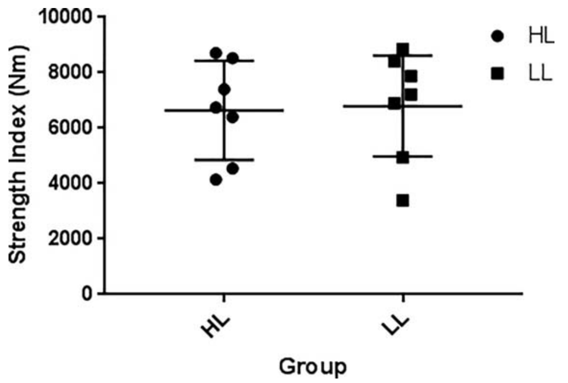

FIGURE 3. Individual responses in absolute change in strength. Data show means and 95% confidence intervals.

intervention, and total time taken to complete each session. A Shapiro–Wilk test was conducted to determine whether data met assumptions of normality of distribution. When assumptions of normality were met, paired samples *t*-tests were used for within-participant comparisons across conditions. For ordinal variables (average RPE-E and average RPE-D), the Wilcoxon signed ranks test was used for within-participant comparisons across the conditions. Wilcoxon signed ranks test was also used to assess changes in conditions between the first and last training sessions for RPE-D.

All statistical analyses were performed using IBM SPSS Statistics for Windows version 20 (IBM Corp., Portsmouth, Hampshire, UK), with $P < 0.05$ considered statistically significant. Further, 95% CIs were calculated to assess significance within conditions for absolute change in strength and repetitions.

RESULTS

Paired-samples *t*-tests revealed no significant difference between HL and LL for baseline strength [$t_{(6)} = 0.462$, $P = 0.660$; HL = 13,971.26 ± 3,538.75 Nm, LL = 13,784.13 ± 3,748.11 Nm] and absolute change in strength [$t_{(6)} = -0.300$, $P = 0.775$; HL = 6,641.88 ± 1,785.60 Nm, LL = 6,798.79 ± 1,965.23 Nm]. The 95% CIs suggested both conditions resulted in significant strength changes. Figure 3 shows absolute change in strength for each condition. Paired-samples *t*-tests revealed a significant difference between HL and LL for average repetitions per set [$t_{(6)} = -11.248$, $P < 0.001$; HL = 9.66 ± 1.94 repetitions, LL = 20.16 ± 4.30 repetitions] and total training time [$t_{(6)} = -11.248$, $P < 0.001$; HL = 351.77 ± 46.45 seconds, LL = 603.77 ± 103.21 seconds]. Paired-samples *t*-tests revealed no significant difference between conditions in the change in repetitions performed per set from week 1 to week 6, although 95% CIs suggested significant within-condition changes for both conditions for all sets. Table 2 shows repetitions per set (mean ± standard deviation) across the duration of the intervention for both HL and LL groups.

As expected, based on our scales and the fact that participants trained to momentary failure, all subjects gave ratings of 10 for RPE-E for every session and set, thus statistical analysis was not performed on this outcome. The Wilcoxon signed rank test revealed a significant difference between HL and LL for RPE-D ($Z = -2.366$, $P = 0.018$; HL = 6.5 ± 2.22, LL = 8.67 ± 0.87).

DISCUSSION

Strength. In this study we have considered the strength adaptations for HL and LL RT. Analyses showed significant and large increases in strength for both groups of recreationally active participants. Our results are consistent with previous research that considered both unilateral exercise in naive participants[5] and bilateral exercise in trained participants[6]; we found that strength adaptations are equivocally the same whether training with HL or LL when repetitions are performed to momentary failure. However, as with previous studies,[5,6] participants performed a significantly higher ($P < 0.05$) volume of training with the LL condition (e.g., repetitions; HL = ~9.7 vs. LL = ~20.2), and it is perhaps worth considering that the mechanism for muscular failure may differ across repetition ranges. For example, Behm *et al.*[33] suggested that momentary failure in HL sets (e.g., 5 RM) occurred as a result of more centrally mediated fatigue (a decrease in number and discharge rates of motor units), whereas momentary failure in LL sets (20 RM) was a result of peripheral neuromuscular fatigue (a decrease in the contractile strength of muscle fibers and mechanisms underlying action potentials[34,35]. Despite the difference in peripheral fatigue with HL and LL training, however, recent work suggested similar central motor outputs.[36]

It is also worth considering that the method of measurement in the current study was independent of training methods (both isometric testing and dynamic training). Fisher *et al.*[9] and Buckner *et al.*[22] recently suggested that using the same testing and training methods (bench press and back squat[37] may permit augmentation of load-specific motor schemata, which would accommodate synchronous recruitment through the use of heavier loads, and may explain the results suggesting greater adaptation as a result of heavier load RT. The body of research in support of similar adaptations for HL and LL training is congruent with our current understanding of the size principle,[38] namely that motor units and corresponding muscle fibers

Table 2. Number of repetitions per set per week by group

Group	Set	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
HL (80% MVIT)	1	10.14 ± 2.54	11.43 ± 1.90	13.29 ± 4.15	14.71 ± 3.95	14.14 ± 3.29	15.43 ± 4.76
	2	7.29 ± 1.80	7.71 ± 1.80	9.00 ± 1.63	9.29 ± 2.21	10.14 ± 2.04	10.29 ± 1.38
	3	5.86 ± 1.57	6.43 ± 1.72	6.43 ± 1.51	6.86 ± 3.08	7.43 ± 2.94	7.57 ± 1.62
LL (50% MVIT)	1	19.43 ± 5.16	23.14 ± 6.84	25.00 ± 8.14	28.57 ± 13.53	34.43 ± 17.31	34.00 ± 15.49
	2	13.43 ± 3.31	14.71 ± 3.40	15.71 ± 3.40	16.57 ± 4.93	17.57 ± 4.58	19.14 ± 6.94
	3	11.29 ± 2.75	11.43 ± 3.05	12.29 ± 4.39	12.71 ± 4.11	12.86 ± 4.10	15.86 ± 5.76

Data expressed as mean ± standard deviation. HL, heavy load; LL, light load.

are sequentially recruited from the smallest to the largest to maintain or increase force.

We should also consider the potential limitations of this study, including the unilateral, within-participant design. Although this controls for sleep, nutrition, genetics, hormonal responses, and potential interindividual perceptions of effort and discomfort, it may be hindered by chronic neurological adaptations to training, such as cross-education, and acute responses, such as non-local muscular fatigue (NLMF). One meta-analysis suggested that cross-educational effects of unilateral training can result in an absolute strength increase of 7.8% in a contralateral limb.[39] However, these values were reported for adaptations of an untrained limb hypothesized to result from facilitation of the motor cortex. Because participants in this study trained both limbs to momentary failure and that effort is thought to originate in the primary motor cortex,[14,39] it seems more likely that these adaptations are a result of maximal effort resistance exercise irrespective of load rather than cross-education.

Behm *et al.*[33] previously reported that momentary failure in sets of around 5 repetitions resulted from more centrally mediated fatigue, whereas sets of around 20 repetitions were a result of peripheral neuromuscular fatigue. Thus, the HL condition may have enhanced the LL condition as a result of centrally mediated neural factors through NLMF,[40] especially in recreationally active (but currently untrained) participants, where neural adaptations may be more prominent. However, we should be cautious in making the assumption that NLMF had any effect. For example, within our study, the HL condition used a moderate load of ~9.7 repetitions per set (greater than the 5 RM used by Behm *et al.*[33]). Furthermore, the studies suggesting NLMF in the knee extensors[41] used only 2 minutes between fatiguing and testing contralateral limbs, whereas our study included a 15-minute rest interval. Although one could argue that NLMF may have been a factor, the rest interval applied, along with the alternation of HL and LL training performed first in each session, likely minimized any chronic adaptations resulting from NLMF. It may be pragmatic to conclude that, although the strength outcomes were similar in each condition, the mechanisms underpinning these adaptations may have been different.

Effort and Discomfort. Notably, no analyses were performed on values for effort, as all participants reported maximal values for each set and session of exercise. This was to be expected, as the RPE-E scale used is anchored at momentary failure as maximal. This provides a platform to control effort as maximal and determine perceptual differences in discomfort between HL and LL conditions. Furthermore, one can compare effort and discomfort with instruction for differentiation between these perceptions provided to participants. Comparison of HL and LL conditions revealed a statistically significant difference in favor of a higher degree of discomfort (RPE-D) for the LL training group (RPE-D; LL = 6.5 vs. HL = 8.7).

Earlier studies of RPE in RT have yielded peculiar data, possibly due to application of RPE scales in RT using descriptors/anchors based on load, and also due to conflation of discomfort.[27] As noted earlier, in this study, we anchored our maximum RPE-E ratings based on participants reaching momentary failure—in essence, the point at which the trainee is unable to meet and overcome the demands of the exercise despite the greatest effort. We also used scripts that permitted participants to differentiate between effort and discomfort. Our data corroborate previous publications suggesting higher values for RPE (using traditional scales) when training to momentary failure with a lighter, compared with heavier, load.[9,18,20] As mentioned, this is likely due to the higher number of repetitions[15] and longer time under muscular tension.[16] This suggests these earlier reports of RPE were likely influenced by participants' perceptions of discomfort. We found that a significantly greater number of repetitions per set (HL = ~9.7 vs. LL = ~20.2) and significantly longer total training time (HL = ~352 seconds vs. LL = ~604 seconds) for the LL condition further support this hypothesis.

Because both HL and LL conditions improved their strength to a similar degree, it is important to consider the higher values for discomfort for the LL intervention group. This study adds to the body of research suggesting the same increases in muscular strength occur when training with HL and LL.[1,5–7] However, participants may be more encouraged to consider the use of HL RT if there is a lower degree of discomfort, particularly if the ability to reach momentary failure is potentially hindered by a higher degree of discomfort.[9]

Although we did not measure metabolite accumulation, we can speculate on the possibility of different metabolic stresses resulting from the HL and LL interventions. As stated previously, the body of research suggests that, at HL, it is central fatigue that catalyzes the inability to stimulate the motor neurons that activate muscle fibers. On the other hand, LL peripheral fatigue is likely the cause of exercise cessation [resulting from a combination of insufficient adenosine triphosphate (ATP), low pH, and inability to transmit the impulse across the neuromuscular junction]. The body of research indicates that, for LL and/or longer muscle contractions, there are increases in inorganic phosphate (P_i) along with increases in H^+ (as a result of the prolonged ATP production), and thus concurrent decreases in intramuscular pH.[42–44] Various investigators have reported correlations between muscle hypertrophy and changes in P_i ($r = 0.876$) and intramuscular pH ($r = 0.601$) after LL resistance training.[44] It is likely these increases in metabolic stresses resulted in the higher values for discomfort for the LL group in our study. Perceived effort is likely centrally mediated, whereas perceptions of discomfort may be more closely associated with afferent feedback.[14] If the intention is to reach maximum effort (i.e., muscular failure) with an LL (and thus optimize muscle fiber recruitment and adaptation), then these metabolic stresses, afferent feedback, and resulting increased discomfort may be inevitable.

It remains possible that a habituation effect occurs as the result of repeated exposure to discomfort associated with LL training. Repeated exposure to painful stimuli has been suggested to be mediated by changes in central processing of painful stimuli.[45] Over the duration of our intervention there did not seem to be any habituation in terms of reduced discomfort for either condition, as the differences between first and last session average RPE-D were within the expected error for these variables[27] (first session: HL = 5.9, LL = 8.4; last session: HL = 6.9, LL = 9.2). However, this may have been due to the length of the intervention (6 weeks), and habituation may be more likely to occur over longer time periods. Participants' previous training experiences were not considered in detail, which may have influenced the degree to which they habituated, although none had been engaged in structured RT for at least 6 months before the study. Future research should consider whether there is habituation to the discomfort associated with these training conditions, particularly LL.

Finally, we should recognize the limitation that we did not consider female participants in this study, thus the data reported cannot be generalized to women. Future research should consider comparisons between men and women for chronic strength increases as well as acute responses to resistance exercise, including ratings of effort and discomfort, with both HL and LL conditions.

In conclusion, in this study we have presented data that should be considered by coaches, trainers, and trainees alike; RT with HL and LL produces similar strength increases, although possibly through different mechanisms. This permits self-selection of a load rather than the necessity to use heavier loads to attain desired physiological adaptations. However, individuals should consider the potential for a greater degree of discomfort as a result of larger volume (repetitions) and longer time under load when exercising to momentary failure with lighter loads, as well as better time efficiency associated with HL RT. Athletes who perform sport-specific training may better be prescribed RT, which incurs a lower degree of discomfort so as not to interfere with higher priority sessions. Furthermore, lay persons may elect to use HL so as not to incur the possibly debilitating effects, which may be associated with increased discomfort. Conversely, some may prefer training to momentary failure with LL due to a lower perceived risk of orthopedic injuries, or when rehabilitating musculoskeletal injuries, as strength adaptations are similar whether using HL or LL. Taken together, these results show that a range of loads can be used, based on personal preferences.

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